GCM - Ice Sheet Coupling:
Generating Hi-Res Suface Mass Balance Fields with a GCM.

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What?

Two-way coupling of ModelE and a dynamic ice sheet model

- Drive ice sheet surface mass balance with GCM.
- Feed ice extent changes back into ice sheet model.

Outline

1. Introduction and Overview
2. Height Classes

    - Downscaling (Extrapolation)
    - Examples and Evaluation

3. Snowdrift (QP) Smoothing
4. Conclusions and Future Work

Why Couple GCMs and Ice Models?

Ice is melting at alarming rates. Address issues like:

- Melting of Greenland
- Sensitivity to climate change of West Antarctic Ice Sheet
- Ice sheet albedo feedback
- Ice sheet inception
- Paleo-climate studies of glaciations
- ...[your ice problem here]...

[Photos by Gary Braasch]

Bob Fischer

ICE-GCM Feedbacks

Atmosphere Feedbacks:

- **Albedo feedback:** Warmer temperatures result in increased melting, a darker surface, and additional warming.
- **Ice geometry feedbacks:** As an ice sheet shrinks, its surface warms (temperature-elevation feedback), and regional circulation can change (e.g., Ridley et al. 2005).

Ocean Feedbacks:

- Sub-shelf growth and melting rates depend on time- varying interactions among various water masses, including glacier meltwater.
- Sub-shelf circulations are likely to change as ice shelves advance and retreat over complex topography.

[Slide from William Lipscomb]

One-Way vs. Two-Way Coupling

One-Way Coupling: Drive ice sheet surface mass balance with GCM.

- Model and forecast ice sheet SMB.
- Neglects feedbacks.
- Good up to decadal timescales.
- CESM 1.0, RACMO2

Two-Way Coupling: Also feed ice extent changes back into ice sheet model.

- Model long-term changes in ice sheet.
- Constants must vary: ice extent, ice sheet thickness, land surface type, bedrock topography (?).
- Capture climate feedbacks.
- Good for hundreds or thousands of years.

Studies of long-term evolution of ice sheet require two-way coupling.

Our GCM and Ice Model

GCM: GISS ModelE

Ice Model: CISM provides common interface to multiple dynamical cores:

- **Glimmer**
  - Shallow Ice Approximation
- **SeaCISM** (K. Evans, A. Salinger, S. Price, P. Worley, et al)
  - 3-D higher-order velocity solver
- **BISICLES** (D. Martin, S. Cornford, et al)
  - 2-D higher-order velocity solver
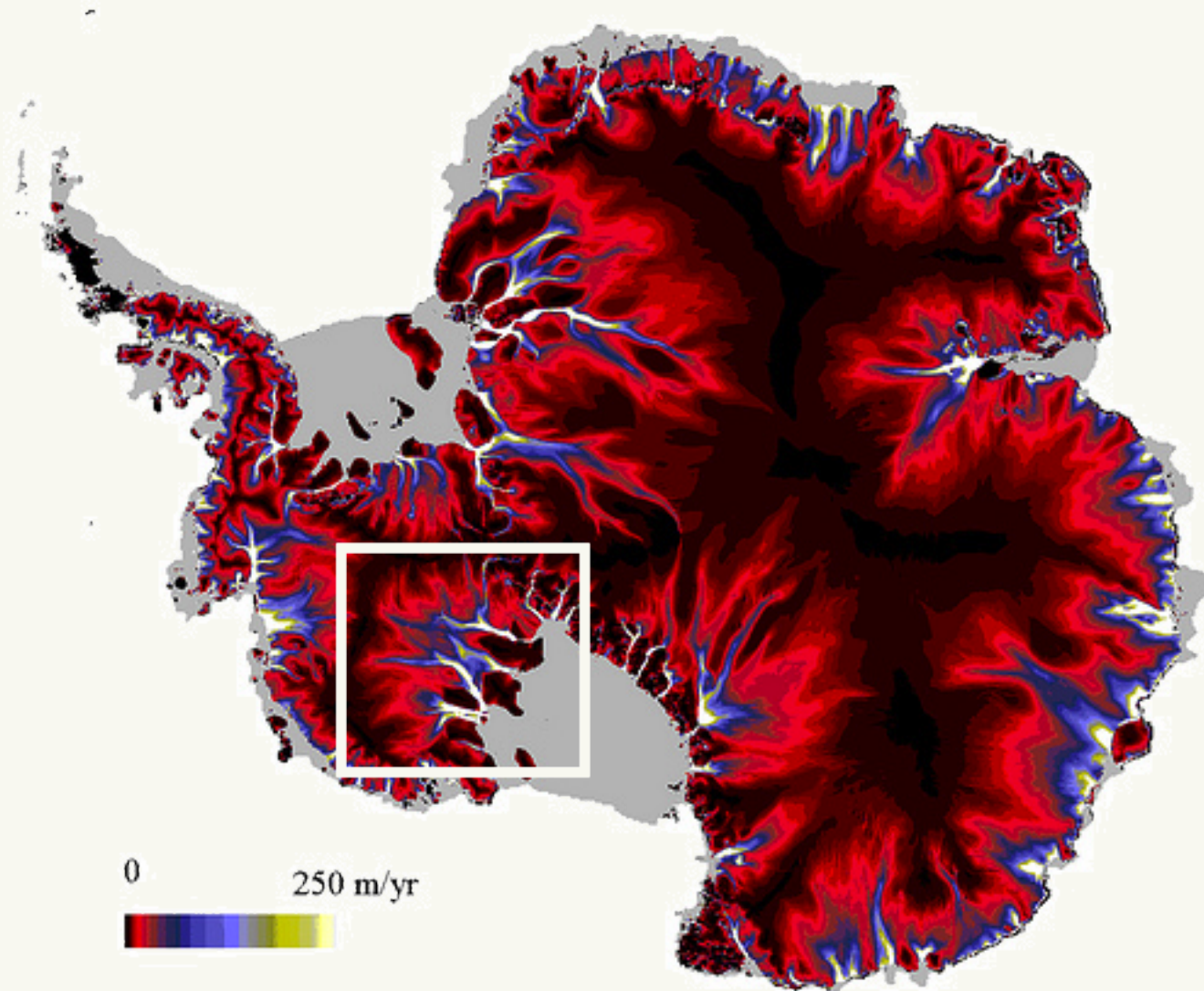 - Adaptive Mesh Refinement

Other Ice Models: ISSM, PISM, etc.

- Content of this talk applies to all ice models

[Slide adapted from William Lipscomb]
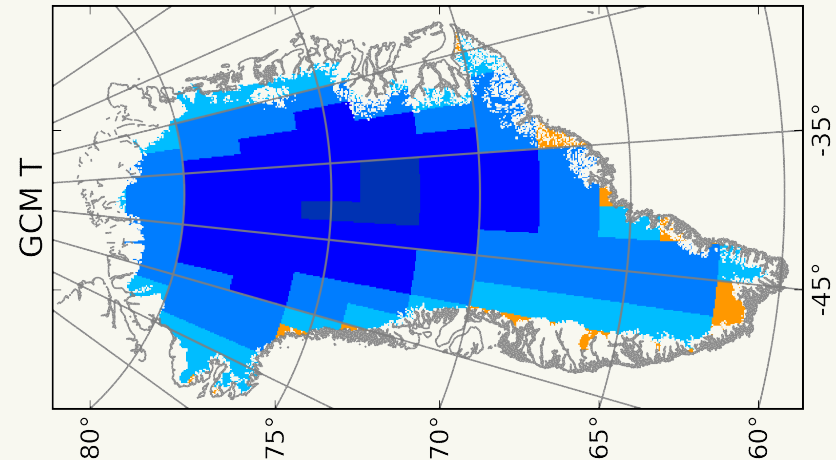
A Dynamic Ice Model
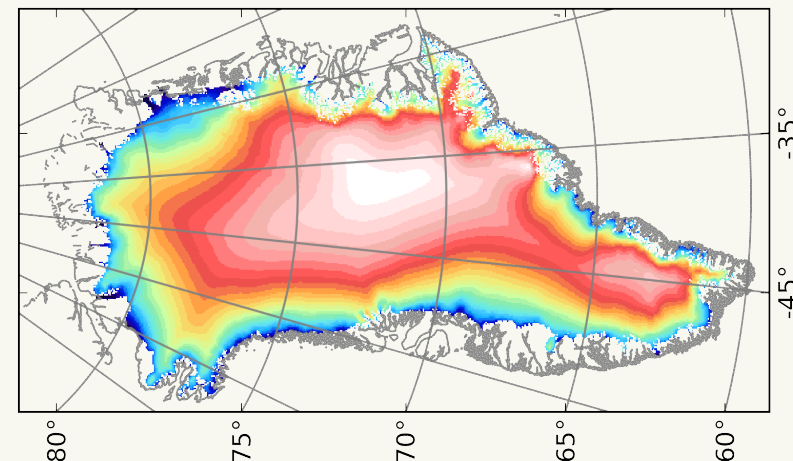
Example from ISSM (Bamber)

Challenges

1. Model Mismatch

   - **ModelE:** Lo-Res, Short Timestep, Round Earth
   - **Ice Models:** Hi-Res, Long Timestep, Flat Earth

2. Precipitation critical to correct surface mass balance (SMB).
3. Ice model needs hi-res SMB
4. Narrow outlet glaciers (1-km resolution needed).
5. Unknown basal properties.
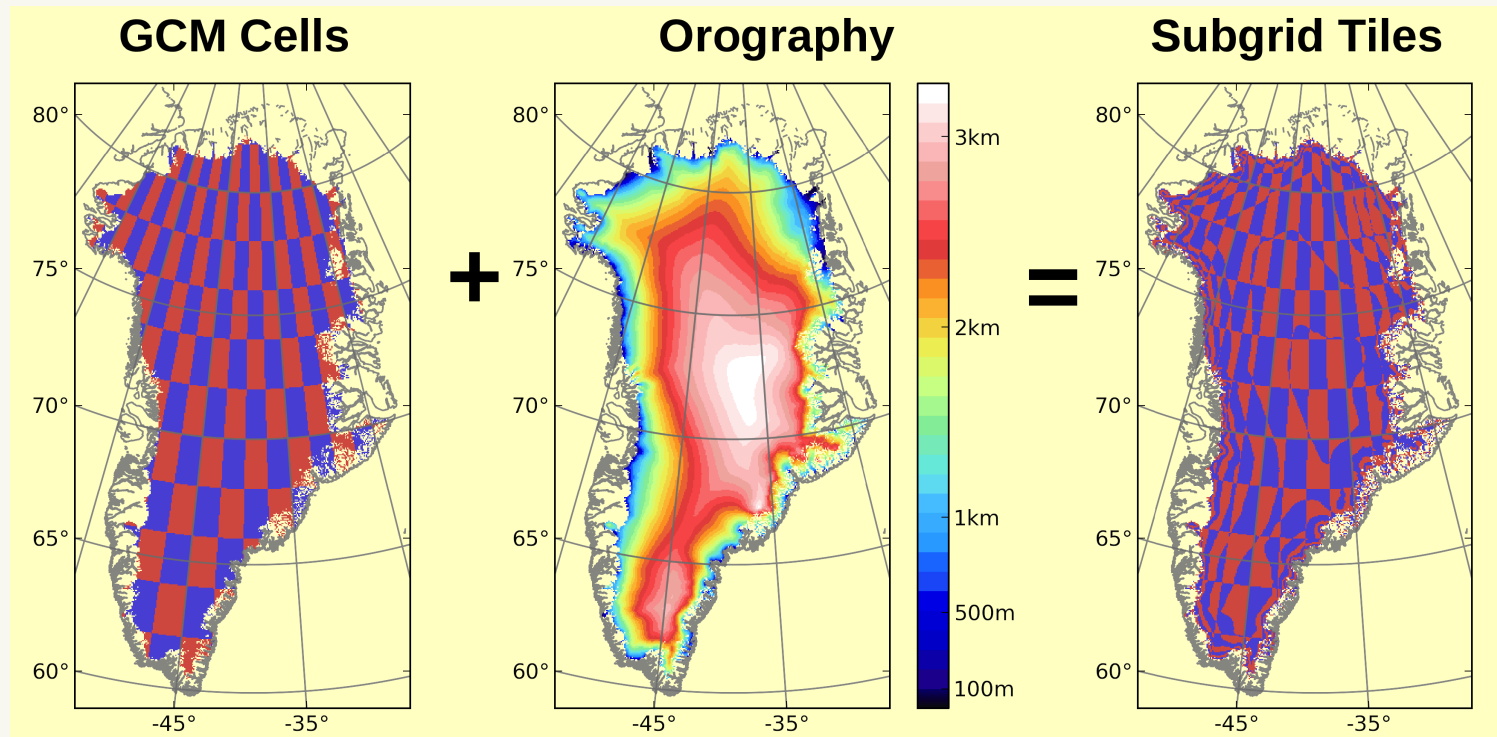6. Ice Shelves

GCM View of World

Ice Model View of World

Height (Elevation) Classes

- Medium-res grid inbetween GCM (coarse) and ice (fine).
- GCM grid cells sub-divided based on elevation.
- GCM keeps state on a per-height-class basis
  (like n more land surface types).

Downscaling with Height Classes

Atmosphere values extrapolated ("downscaled") to height-classified grid based on elevation.

- **Pressure:**

$$P = P_0 e^{-(z-z_0)/H}$$

  . . . where H is scale height of atmosphere

- **Temperature:**

$$T = T_0 - \alpha(z - z_0)$$

  . . . where α is an adiabatic lapse rate ($\approx 4 - 8K$/km)
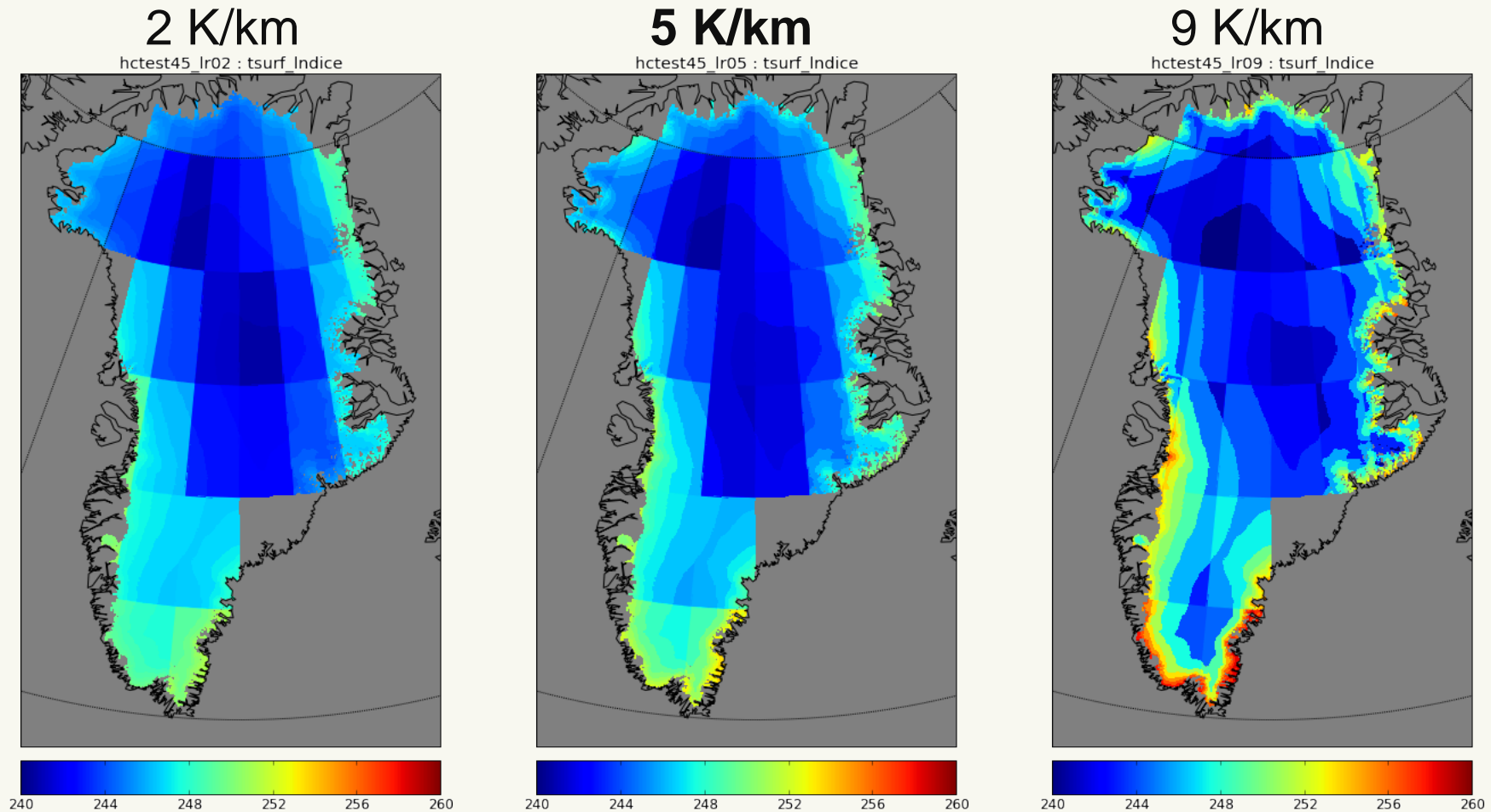
- **Precipitation:** None for now.

  - Probably needed in future.
  - Downscaling schemes exist, not so much in GCM context.

Question: Are these extrapolations "reasonable?"

Question: What lapse rate to use in T downscaling?
(Constant over space and time).
Answer: Try a bunch, pick the one that generates smoothest T fields.

2 K/km

hctest45_lr02 : tsurf_Indice

5 K/km

hctest45_lr05 : tsurf_Indice

9 K/km

hctest45_lr09 : tsurf_Indice

Question: Maybe we could be more sophisticated in T downscaling?

What goes into Surface Mass Balance (SMB) Computation?
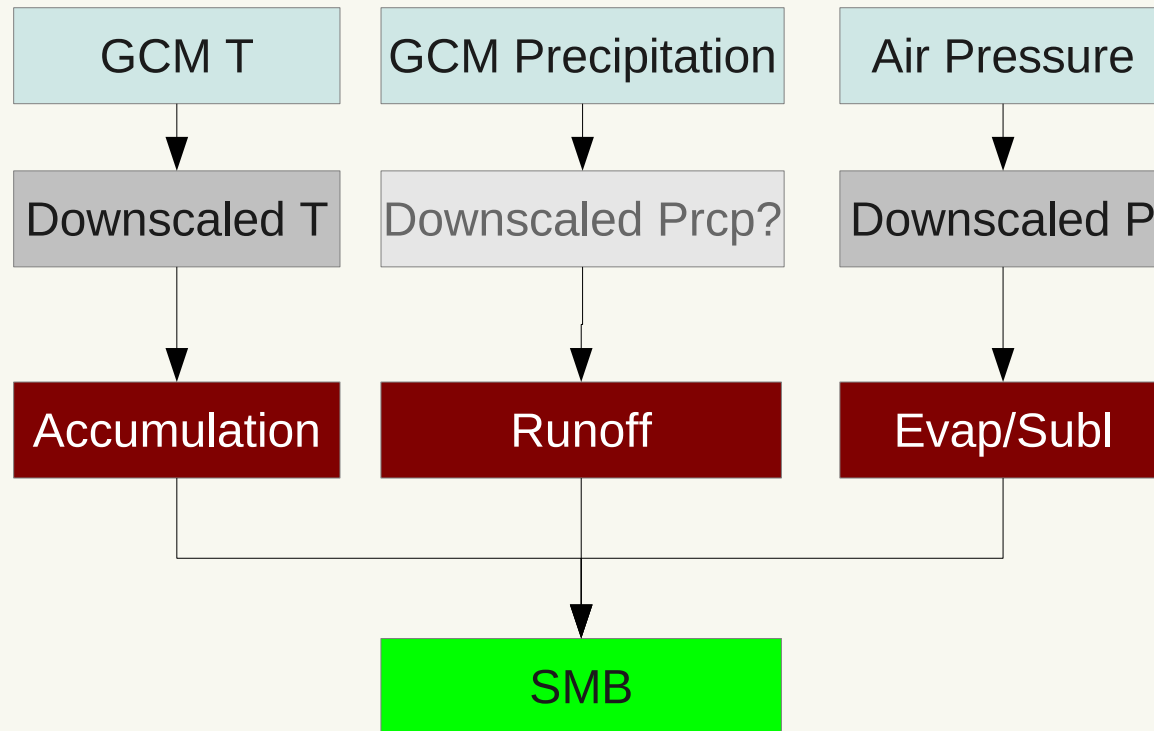
- Are height classes necessary to generate realistic SMB fields from GCM?
- How well can we represent real SMB fields?
- How good are the SMB fields we can generate?

Question: Are height classes necessary to generate realistic SMB fields from GCM?

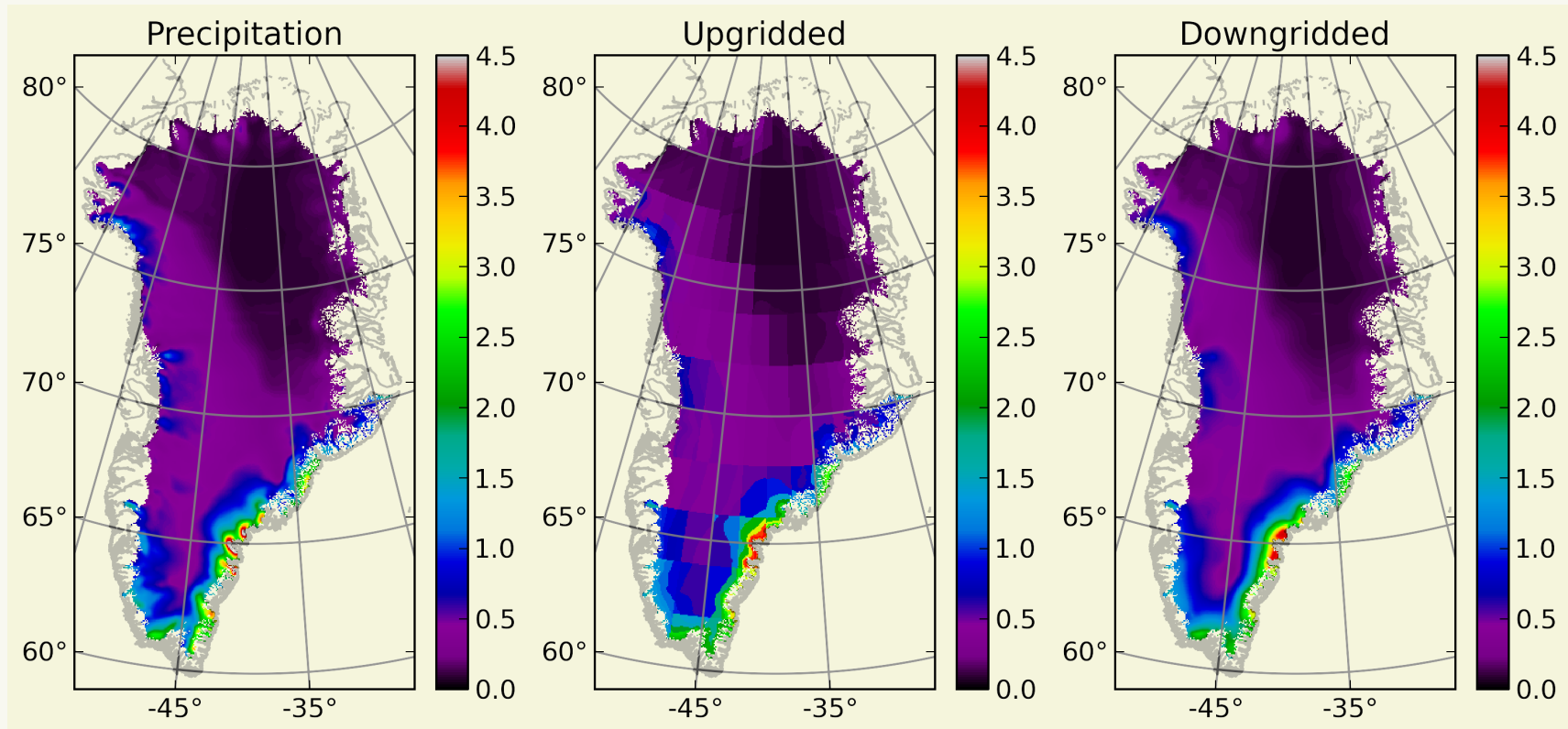**Answer:** YES! Without height classes:

- Margins of ice sheet — the action! — cannot be resolved.
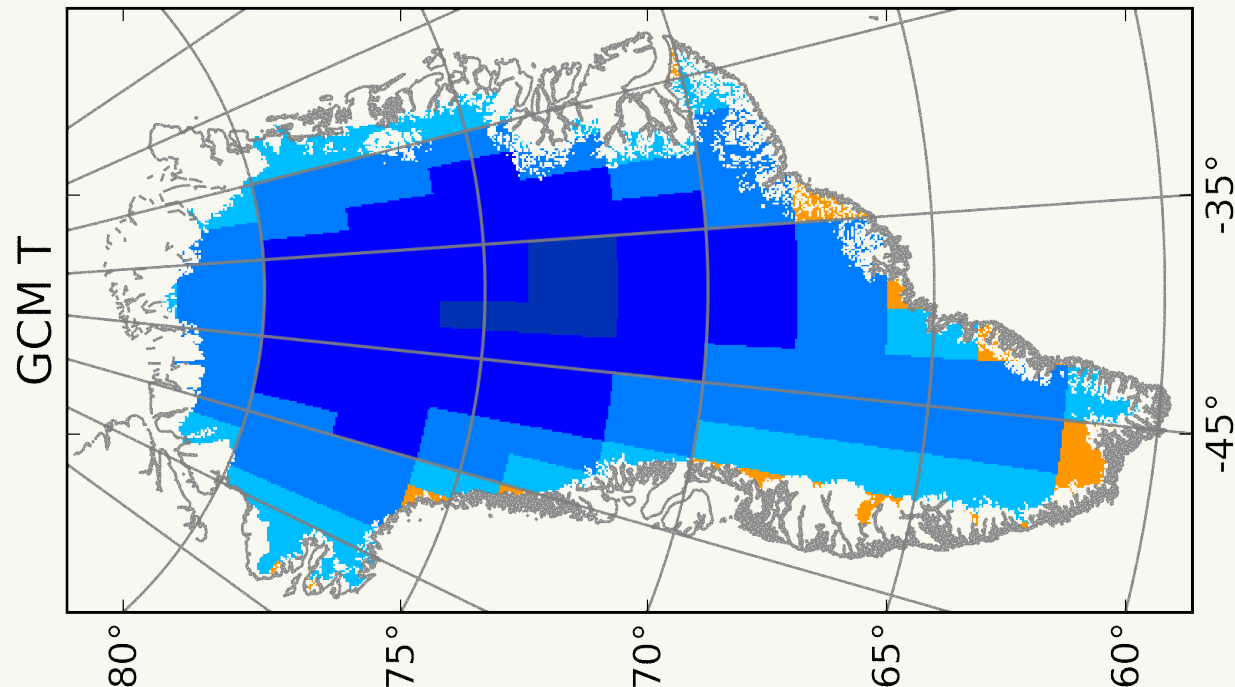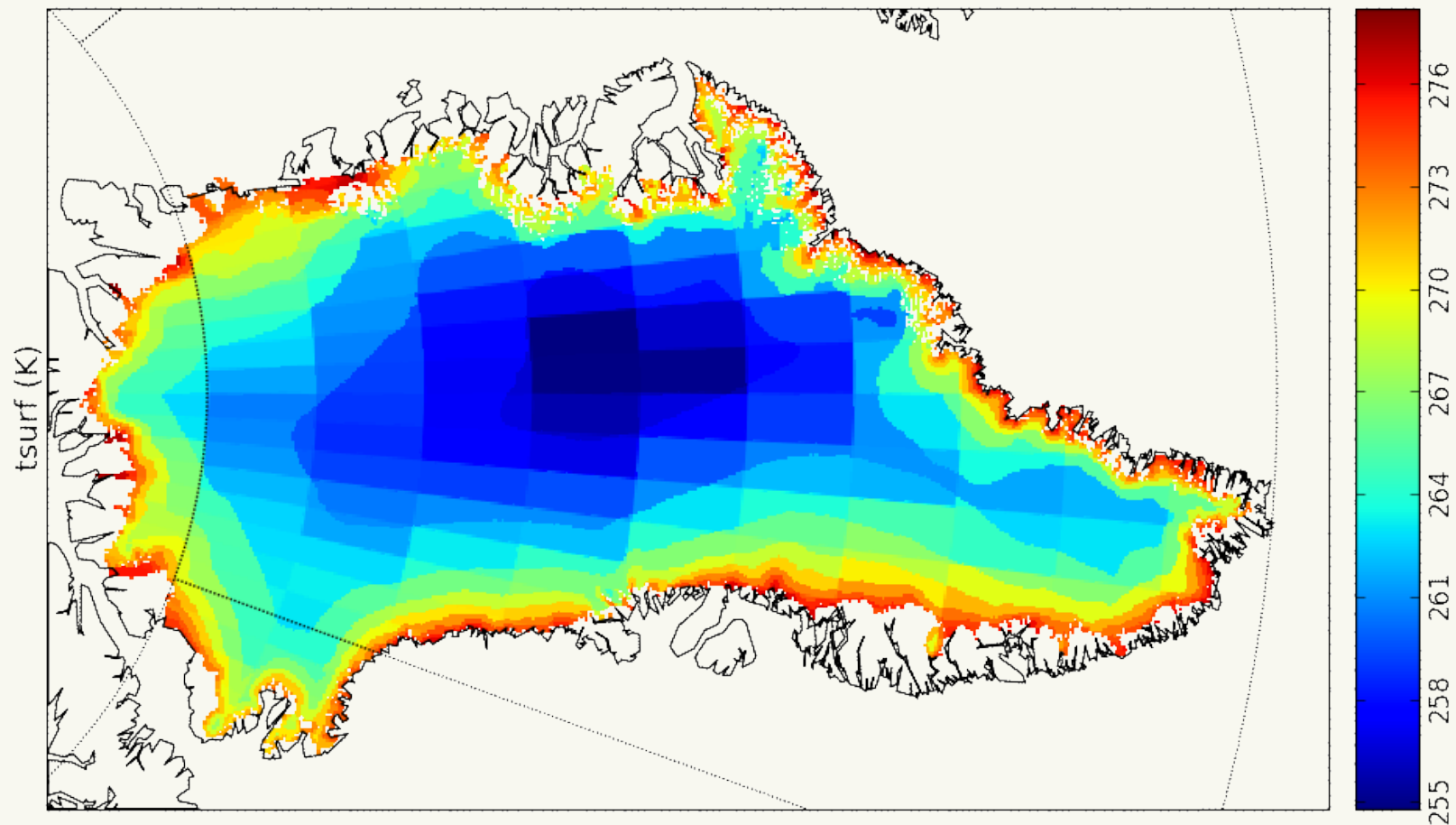
Height Classes: Representation

Question: How well can we represent real SMB fields?
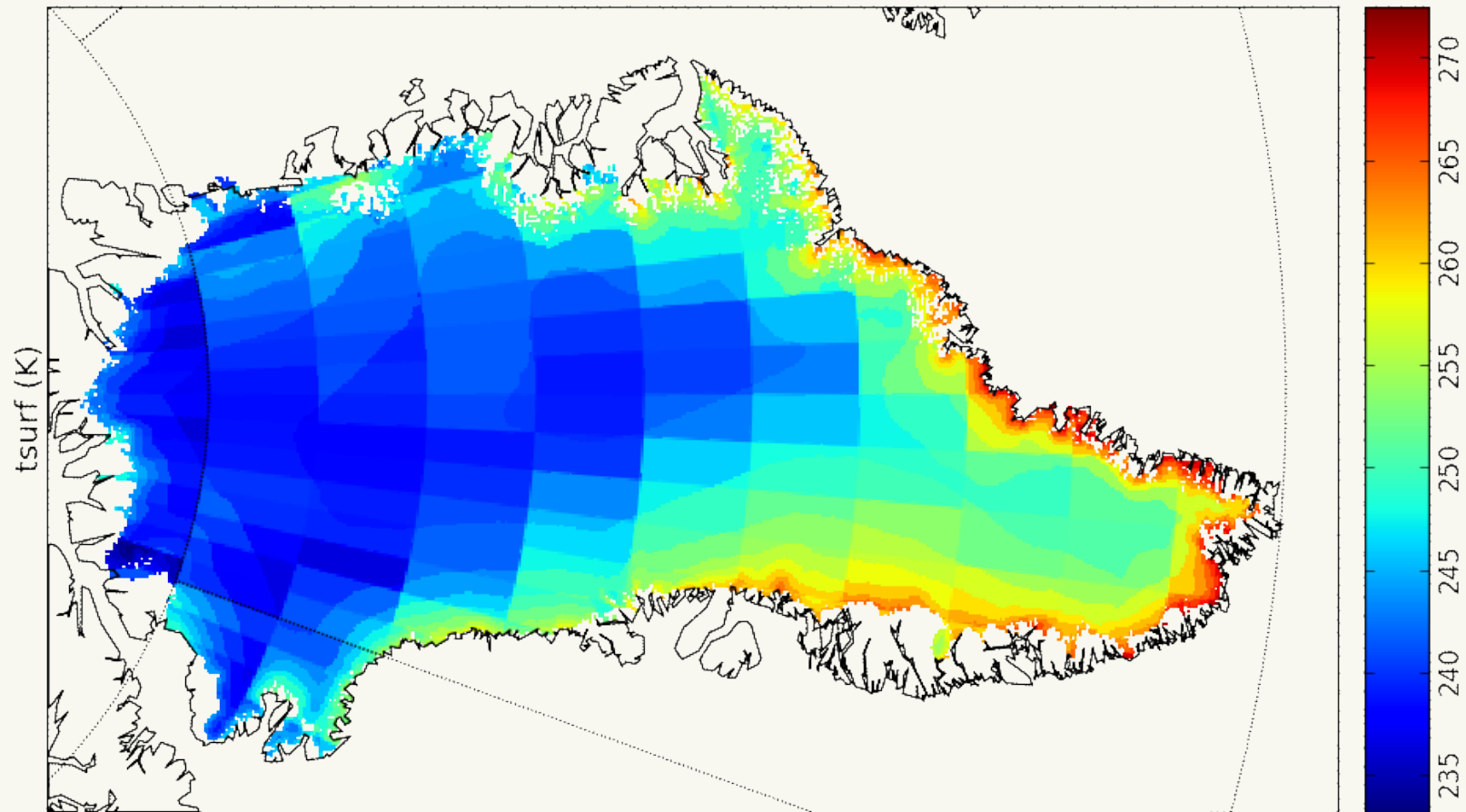**Answer:** Let's try representing RACMO2 precipitation with height-classified grid.

Question: How good are the SMB fields we can generate?

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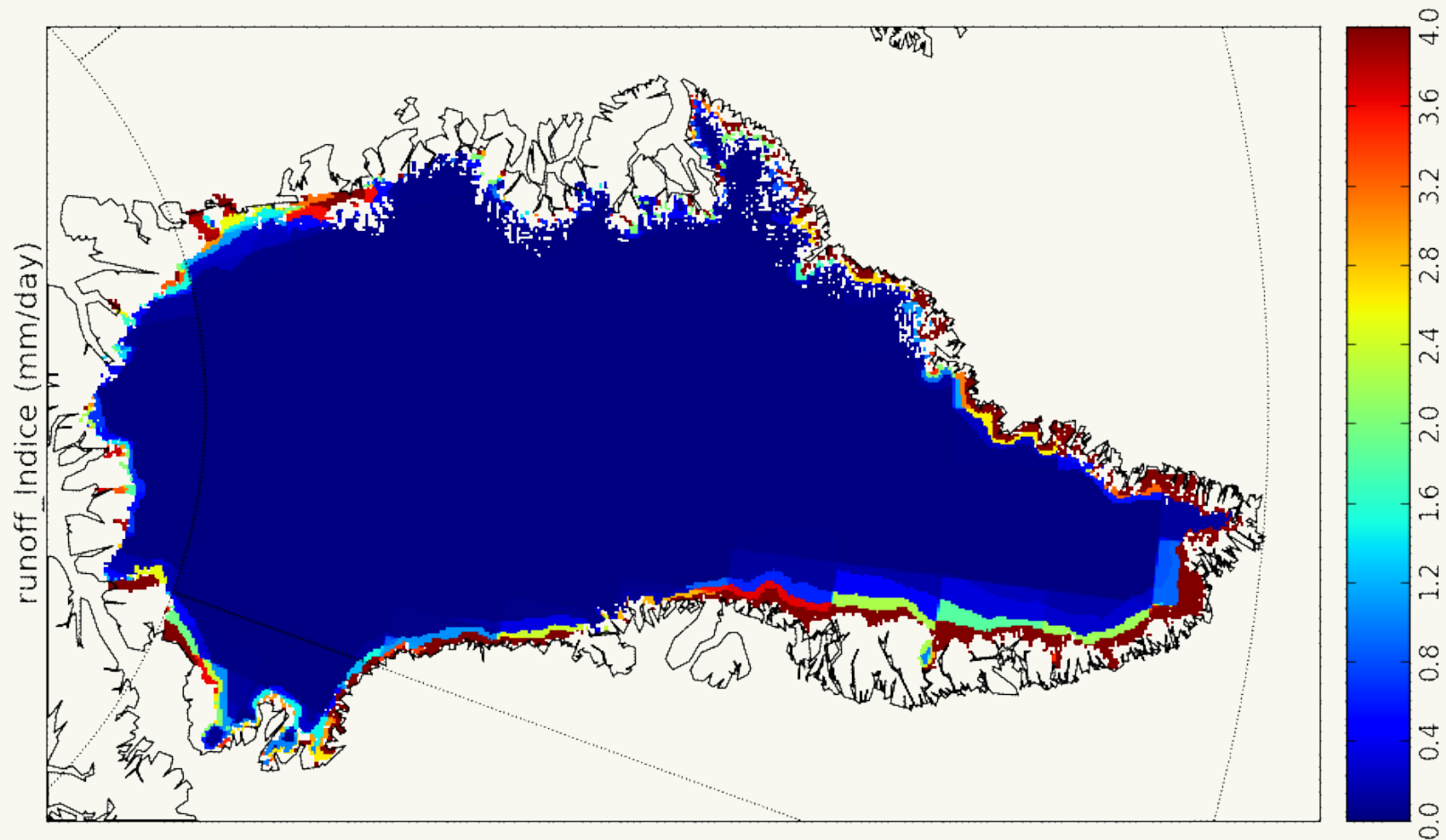
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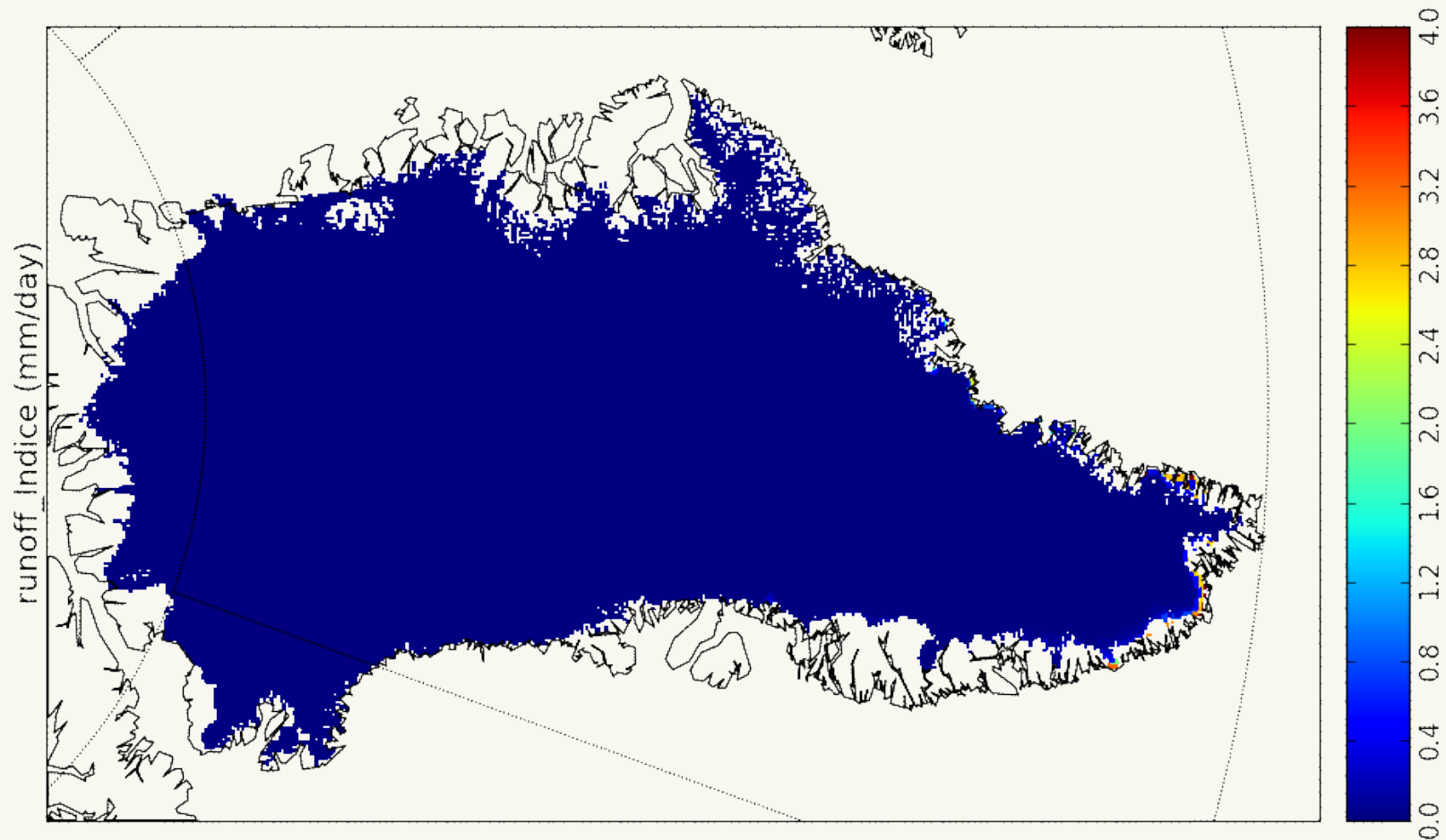
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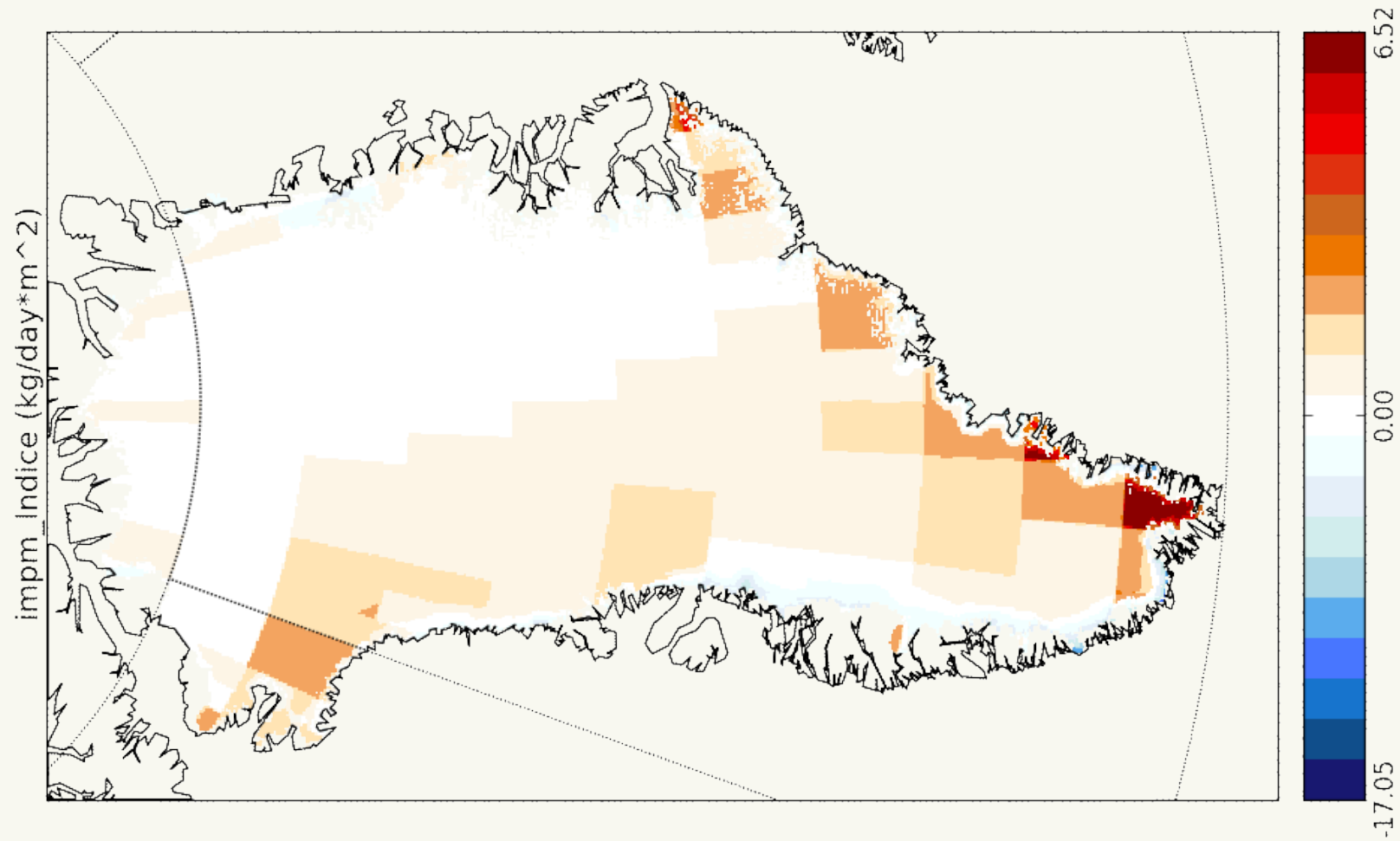
But is it Smooth?

Ice models want *smooth* (5km) SMB input.

- Must maintain conservation of mass and energy when smoothing.

Bilinear Interpolation:

- Not easily conservative.

Snowdrift (QP) Regridding:

- New smoothing algorithm that maintains conservation.
- Finds smoothest field that satisfies conservation requirement.
- Fundamentally different from other smoothing schemes.

Overlap Matrix

- Related to Exchange Grid (ESMF)

Sample Grid Pair

Sample Overlap Matrix L_{ij}

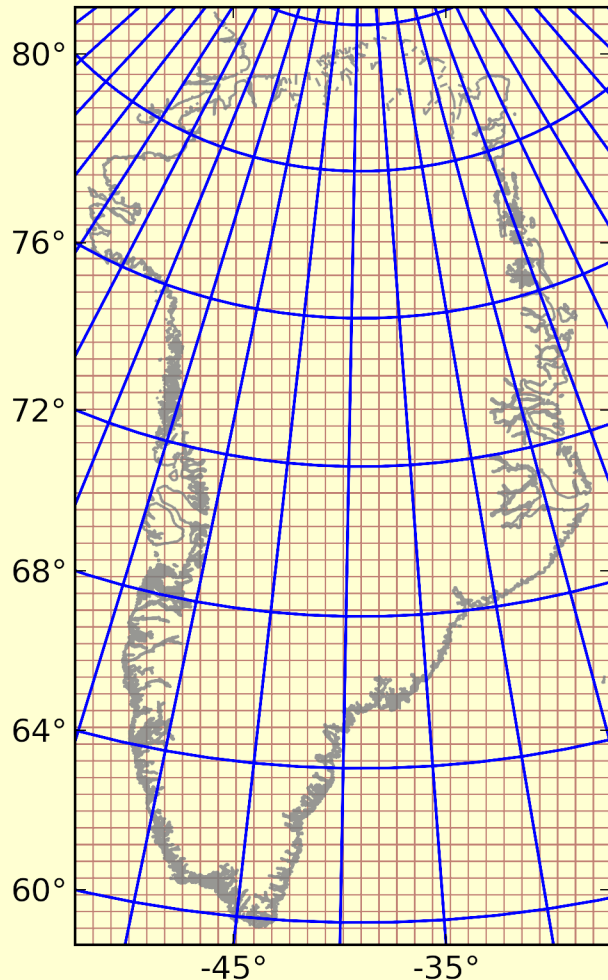|	1	2	3	4	5	6	7	8	9
1	1	0.5			0.5	0.25			
2		0.5	1			0.25	0.5		
3				0.5	0.25			1	0.5
4					0.25	0.5		0.5	1

G = GCM grid, $G_{i=1...m}$ = polygons
H = ice grid, $H_{j=1...n}$ = polygons
L_{ij} = Overlap Matrix = $|G_i \cap H_j|$

- Overlap Matrix is sparse
- General Polygon Algos used to compute L_{ij}
- Works for all grid geometries (ice & GCM)

Simple Conservative Regridding

Multiply by Overlap Matrix

Upgridding (Ice → GCM)

$$Z_{G_i} = \frac{L_{ij} Z_{H_j}}{\sum_j L_{ij}}$$

Downgridding (GCM → Ice)

$$Z_{H_j} = \frac{Z_{G_i} L_{ij}}{\sum_i L_{ij}}$$

Most regridders = Matrix Multiply
(for some matrix)

Downscaling is choppy, Ice model needs smooth input.

Problem Requirements:

- Smooth Field Required
  $\Rightarrow$ minimize $|\nabla Z|^2$ over the ice sheet

- Conservation Required.

  $\Rightarrow \displaystyle\int_{C_i} Z \, dA$ conserved through regridding

  (for conservation regions C_i)

Phrase as Quadratic Program:

Minimize (with respect to $\mathbf{x}$):
$$f(\mathbf{x}) = \tfrac{1}{2}\mathbf{x}^T Q \mathbf{x} + \mathbf{c}^T \mathbf{x}$$
Subject to constraints of the form:
$$A\mathbf{x} \leq \mathbf{b} \text{ (inequality constraint)}$$
$$E\mathbf{x} = \mathbf{d} \text{ (equality constratint)}$$

Solve the Quadratic Program

- Conjugate Gradient Solver for Equality Constraints
- GALAHD Optimization Package

Conservation Regions

"Conservation" is underdefined. Is regridding:
- Conservative over entire ice sheet? C_1 = {Entire Ice Sheet}
- Conservative over each GCM cell? $C_i = G_i$

Larger conservation regions $\Rightarrow$ more smoothing.

Indications for More Smoothing

- Smaller GCM cells
- Unrealistically choppy downscaling artifacts.

Smoothing is an art!

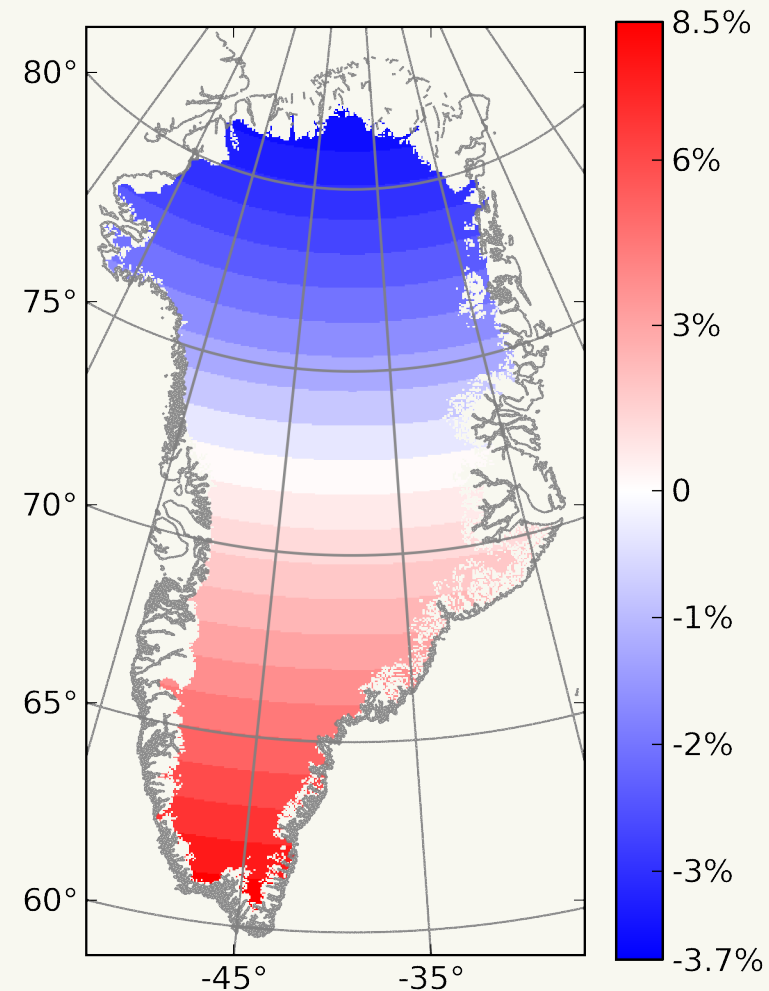...but now we're getting away from the Physics :(

- Geometry Mismatch:
  GCM = *Round Earth*
  Ice Model = *Flat Earth*
- Projection used.
- **Q:** What happens when grid cells change area through projection?
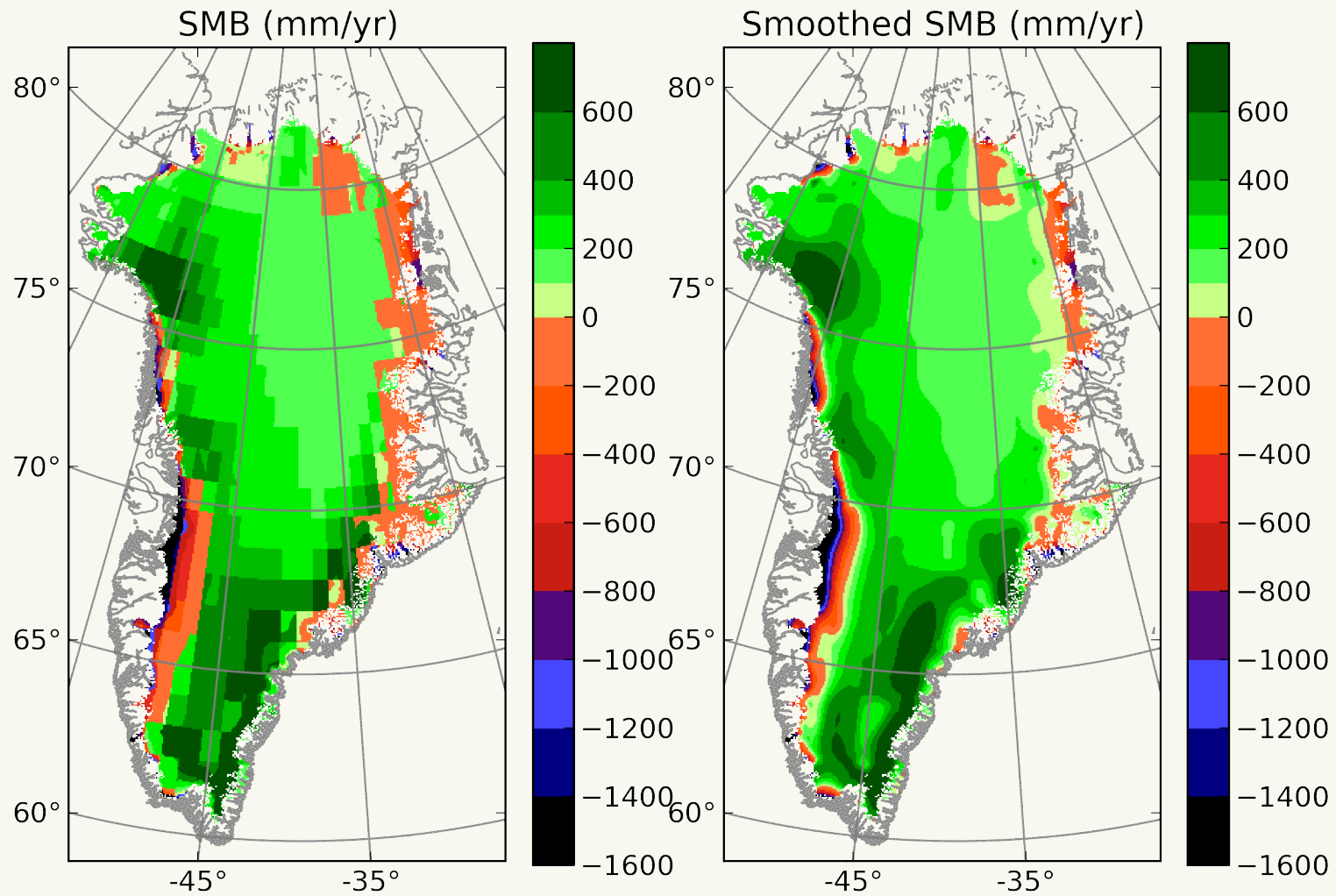
Moral of Story: Use an equal-area projection

- **Lambert Equal Area Azimuthal:** Good!
- **Stereographic:** Bad!

Don't Try This at Home

(Constant field regridded through Stereographic Projection)

Smoothing Example

[Courtesy of CESM (Bill Lipscomb et al)]

Conclusions

- Height classes are critical to producing realistic SMB fields from low-res GCMs.
- Orographic precipitation downscaling will also be needed, especially in non-melting regimes.
- Snowdrift regridding may be an effective way to produce smooth ice model inputs.
- Use equal-area projections in Ice Model - GCM Coupling work.

Future Work

- Try out one-way coupling, just for fun!
- Optimal Height Classes?
    - Current fixed height classes adapted from Lipscomb et al.
    - Can we do better?

- Snow/Firn model on top of dynamic ice model, $15m$ deep.
    - Ice models want constant T on top.
    - Required to keep conservative energy budget.
    - Should be same as snow model over bare land surface types.

- Precipitation Downscaling (Smith, Barstad, et al)
    - Necessary for hi-res SMB in non-melting regime.

- Dynamic Ice Extents
    - Upgrade ModelE for dynamic land surface types and orography.
    - Regrid height-classified variables as ice sheet changes.

Ice Shelves

- Area of active basic modeling research.

Basal Features

- Basal topography, hydrology and roughness critical to behavior of ice sheet.
- Parameters hard to know with much certainty.
- Most outlet glaciers remain unmeasured.

Orographic Precipitation Downscaling

- ...in the context of a GCM
- How to move precipitation between GCM grid cells?